Water Resources Research

RESEARCH ARTICLE
10.1029/2018WR023555

Key Points:
- Lake Dillon, a Colorado reservoir, showed a 2.5 °C warming of surface waters over a period of 35 years caused by climate change
- Lake Dillon showed interannual accumulation of heat in the hypolimnion, but the agent of deep warming was tributary waters, rather than interannual warming from the lake surface
- Warming of Lake Dillon did not cause change in thickness of the mixed layer or duration of ice cover; the low temperature of this mountain lake (2,750 m amsl) caused the mixed layer to show irregularity in depth rather than an interannual trend in depth

Supporting Information:
- Supporting Information S1
- Data Set S1

Correspondence to:
W. M. Lewis Jr,
william.lewis@colorado.edu

Citation:
Lewis, W. M., Jr, McCutchan, J. H., Jr, & Roberson, J. (2019). Effects of climatic change on temperature and thermal structure of a mountain reservoir. *Water Resources Research*, *55*, 1988–1999. https://doi.org/10.1029/2018WR023555

Received 5 JUL 2018
Accepted 12 DEC 2018
Accepted article online 7 JAN 2019
Published online 12 MAR 2019

Effects of Climatic Change on Temperature and Thermal Structure of a Mountain Reservoir

William M. Lewis Jr[1,2], James H. McCutchan Jr[1], and Jennifer Roberson[1]

[1]Center for Limnology, Cooperative Institute for Research in Environmental Sciences, University of Colorado Boulder, Boulder, CO, USA, [2]Department of Ecology and Evolutionary Biology, 334 UCB, University of Colorado Boulder, Boulder, CO, USA

Abstract A 35-year monitoring record for the water column of Lake Dillon, a reservoir of the southern Rocky Mountains, shows near-surface warming of 0.76 °C/decade and warming at all greater depths (55 m); warming was progressively smaller with depth. Annual heat budget of the lake increased (67 cal·cm^{-2}·year^{-1}; 0.089 W/m^2) as did Schmidt stability (41%). The mixed layer was affected by climatic conditions at the high elevation of the lake (2,750 m above mean sea level); heat fluxes were high during both the seasonal warming and cooling. Density gradients below the mixed layer were weak because of low water temperatures associated with high elevation. Annual cooling of the mixed layer was rapid following a brief initial stabilization and showed high interannual variability across years for a given month, which obscured any trend in mixed layer thickness that might have been caused by heat accumulation. The hypolimnion was warmed by advective heat exchange from tributary inflow and deep water withdrawal, not by carryover of fall or spring warming; advective warming by tributaries can be expected in many reservoirs.

Plain Language Summary Lake Dillon, a mountain reservoir in Colorado, showed a high degree of surface warming (2.5 °C) over a 35-year interval as a result of climate change. Reservoirs have not been studied for response to climatic warming. Release of water from the bottom of the lake, which is common for reservoirs, caused Lake Dillon to show warming of deep water caused by replacement of cool water withdrawn through the outlet by inflowing river water, which showed climatic warming over the 35 years. Lake Dillon, which has higher elevation (2,750 m above mean sea level) than other lakes that have been studied for response to warming, did not show change in thickness of its surface layer (epilimnion) in response to warming, as expected at lower elevation, because the low surface temperatures of Lake Dillon cause irregularity in thickness of the mixed layer that overwhelms any tendency for the epilimnetic thickness to change in response to climate warming.

1. Introduction

Responses to climatic warming for lakes vary with latitude and elevation, lake depth and area, mixing regime, and water quality (Adrian et al., 2009; Goldman et al., 2013; Kraemer et al., 2015; Livingstone et al., 2005; Palmer et al., 2014; Richardson et al., 2017). The present study of Lake Dillon documents another variable, hypolimnetic water withdrawal, which occurs in very few natural lakes but in many reservoirs and has the potential to affect responses to warming in ways that are specific to reservoirs. Water column responses of reservoirs to warming have not been studied. The Lake Dillon record also broadens the scope of current information on elevation as a factor affecting the response of lakes to warming. The effects of elevation have been studied (Livingstone et al., 2005, surface temperature responses up to ~2,500 m; Šporka et al., 2006, up to 2,160 m) but less intensively than other major factors influencing response of lakes to warming and mostly in terms of lake surface temperatures. At 2,748 m above mean sea level, Lake Dillon lies above mountain lakes that have been studied previously for water column responses to warming.

Lake Dillon is a dimictic lake of moderate size (13 km^2) and depth (67 m) with 4 months of ice cover, spring and fall mixing, and 5 months of warm season stratification. It might seem that this mountain lake could be compared in some ways with other mountain lakes that have been thoroughly studied, particularly Lake Zurich (Livingstone, 2003) and Lake Tahoe (Coats et al., 2006), but these lakes are quite different from Lake Dillon in their response to climate warming in that they do not, because of their great depth, develop ice cover (they are warm monomictic) and therefore show an annual minimum water column temperature that varies from year to year and shows interannual trends in response to secular warming, rather than

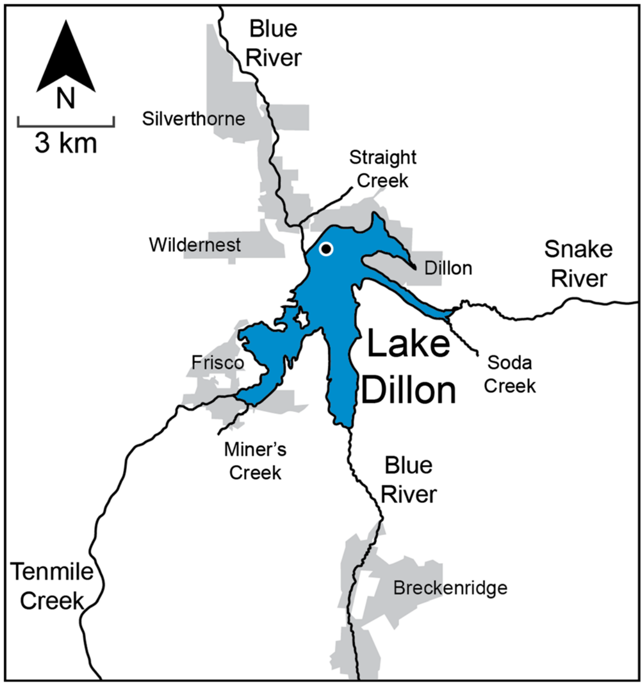

Figure 1. Map of Lake Dillon and surrounding areas; the circle indicates the index station, over deepest water.

returning annually to a temperature near 4 °C. Also, because of their high relative depth, they do not mix completely at the time of annual minimal heat content and in this respect differ from most lakes of temperate latitudes, including Lake Dillon and most other dimictic lakes.

Secular warming of air temperatures in the southern Rockies (0.45–0.93 °C/decade, Mast et al., 2011) is consistent with the warming of Lake Dillon surface water (0.70 °C/decade). Also, small montane lakes in Colorado presently are warming at the surface, as shown by satellite image imagery, at a rate of ~0.47 °C/decade (Roberts et al., 2017). The consequences of climatic warming for lake water column temperatures, however, cannot be determined accurately from changes in air temperatures or water surface temperatures. Synoptic warming of lakes is explained by changes in multiple heat budget components (Fink et al., 2014) and processes that control heat flux (e.g., Schmid & Köster, 2016; Woolway, Dokulil, et al., 2017). Physical responses of lakes to warming are affected by latitude (O'Reilly et al., 2015) and lake morphometry (Kraemer et al., 2015), as well as specific anthropogenic alterations of watersheds (Adrian et al., 2009). The present analysis of Lake Dillon focuses on changes in heat budget and water column stability, thickness of the mixed layer, vertical gradients in rate of temperature change, and the role of advective heat loss in affecting responses of the lake to warming.

The present study of climatic warming for Lake Dillon is based on two hypotheses that can be tested for consistency with the 35-year data record. The first is that hypolimnetic water withdrawal causes the hypolimnion of this and, by implication, other lakes with extensive hypolimnetic withdrawal to be strongly responsive to the warming of inflowing tributary waters and minimally responsive to warming of the upper water column. The second hypothesis, put forth by Livingstone et al. (2005), is that lakes at high elevation, such as Lake Dillon, differ from physically comparable lakes at lower elevation in their response to warming because of their lower water column stability during stratification.

2. Site Description and Methods

Lake Dillon, created in 1963, impounds the Blue River, a tributary of the Colorado River, and two Blue River tributaries, Tenmile Creek and the Snake River (Figure 1). The lake has an area of 13.35 km^2, volume of 0.317 km^3, maximum depth of 67 m, and mean depth of 24 m; spillway level is 2,748 m above mean sea level. The annual hydrograph of the three river tributaries to the reservoir is dominated by snowmelt, which enters the lake primarily between the middle of May and the middle of July. The mean annual hydraulic residence time of Lake Dillon is 1.19 ± 0.29 years. Lewis et al. (1984) give additional information on Lake Dillon and its water sources.

Analysis of layering and mixing as given here employs standard terminology for lake layers: epilimnion (mixed layer), metalimnion, and hypolimnion. The lower boundary of the mixed layer (epilimnion) of Lake Dillon is defined for present purposes as the depth, during the stratification season, at which $\Delta\rho/\Delta z$ is highest. The hypolimnion is defined for the stratification season as the lake volume extending from the bottom of the water column where the lake is deepest up to a depth at which the water column shows a significant temperature gradient (~0.7 °C/m). The layer between the mixed layer and the hypolimnion is the metalimnion.

Lake Dillon was monitored annually during the ice-free season from 1981 to 2016 by use of calibrated thermistors (precision 0.1 °C). In most but not all years, temperature profiles also were taken under ice. Monitoring in most years included approximately 15 sampling dates. Sampling frequency was low for 2 months with unreliable ice cover (for 1981–2016: April, 4 dates; December, 8 dates). Beginning in 2000, monitoring was less frequent in alternate years, for which measurements were made monthly during the ice-free season. Temperatures of tributary rivers were measured as part of the lake sampling program and were combined with U.S. Geological Survey (USGS) temperature monitoring records for the same time

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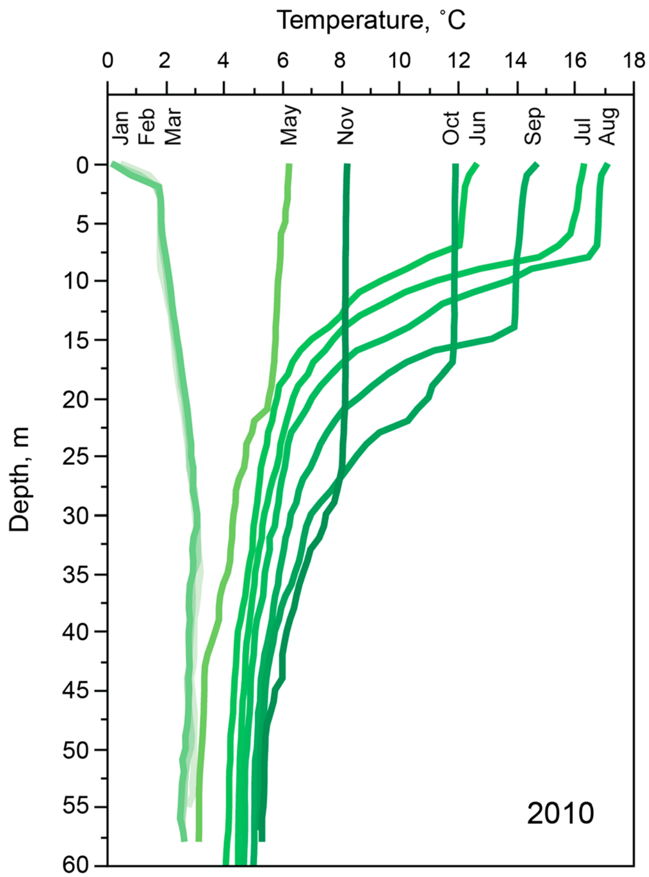

Figure 2. Vertical thermal structure for a specific year (2010), showing a typical seasonal pattern of layer formation and mixing.

span at the three tributary monitoring sites (USGS 09050100, 09046600, and 09047500). The two data sets are complementary in that USGS shows no data after 2004 for the Snake River and Tenmile Creek and no data after 2012 for the Blue River, whereas data for the present study extend to 2016 but show a gap from 1999 to 2006 at the Blue River station.

Additional data of relevance to the analysis of temperature change were collected on each sampling date. Specific conductance was measured over the vertical profile of the lake at 1-m intervals; results show conductance at a standard temperature (20 °C). Transparency was measured as Secchi depth (m). Over a 2-year interval, Secchi depth transparency was calibrated with a PAR (photosynthetically active radiation) quantum sensor, which allows expression of transparency as extinction coefficient, K_t (m^{-1}); the relationship of the two variables is $K_t = 1.7/z_{sd}$.

Heat content of the lake was calculated for all sampling dates by the Birgean method (volume weighted by depth). The annual heat budget is given as the maximum minus the minimum heat content of the lake over the ice-free season ($cal \cdot cm^{-1} \cdot year^{-1}$, W/m^2).

Schmidt stability was calculated for all dates according to the method of Idso (1973, equation 7). Data on total inflow, total outflow, and volume of the reservoir on a daily basis were available from the reservoir operator (Denver Water).

Most of the data analyses were for time series data, for which nonparametric statistics are most appropriate (Helsel & Hirsch, 2002). Bivariate relationships are reported as Mann-Kendall tau (strength of association) and Sen's slope (nature of association). Estimates of probability for nonrandom association follows Mann-Kendall criteria.

Two years of extreme conditions over the 35-year interval of monitoring produced anomalous results for all indicators of heat and water column mixing. The first of these was 1984, a year of severe flooding for which hydraulic residence time of Lake Dillon was very low (0.64 years). The second was 2002, a year of extreme drought during which the reservoir was drawn down to negligible volume. These two years were eliminated from the analyses reported here.

3. Results

Lake Dillon typically had ice cover between late December and April and showed inverse stratification under ice cover (Figure 2). Evidence of stability in layering began to appear in late May, but layering was not well established until June (Figure 2). The mixed layer thickened monthly from late July until late November, when fall mixing occurred (Figure 2).

Vertical distribution of dissolved solids, measured as specific conductance at 20 °C, gives a more detailed picture of vertical mixing in the lake than can be obtained from temperature profiles alone. The lake was fully mixed in November following seasonal stratification, as shown by uniform conductance (Figure 3). By January, vertical divergence in specific conductance was evident; it coincided with the downward flow of winter tributary water, which had higher conductance, and by the influence of melting ice near the surface, together with inverse stratification, which maintained some degree of isolation for waters near the surface. During winter, high conductance of tributary water (e.g., 500 μS/cm) was not fully reflected in the lake because winter tributary flow was small (Figure 4) and, upon entering the lake, mixed with a large volume of water with much lower conductance (e.g., 230 μS/cm).

In April, convergence and increase of conductances over the top 20 m indicate the effects of convective mixing as surface water became more dense in warming from ~2 to 4 °C, but the mixing was weak, as shown by a substantial vertical gradient in conductance below 20 m. Specific conductance in May showed the influence

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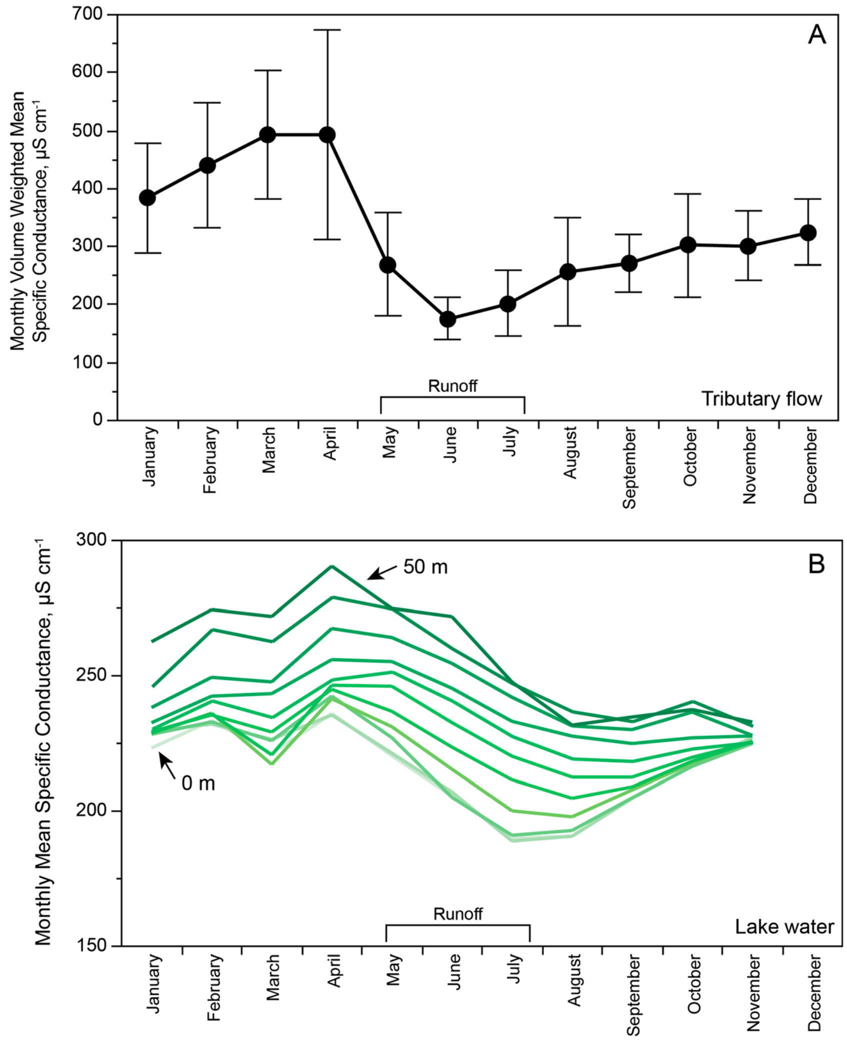

Figure 3. (a) Volume-weighted means and standard deviations for monthly specific conductance of the three river tributaries to Lake Dillon. (b) Mean monthly specific conductance at 20 °C for Lake Dillon, 1989–2016; depths are shown at 5-m increments in darkening color. River conductance is much lower at high discharge (e.g., June at 35 m^3/s) than at low discharge (e.g., January at 6 m^3/s); see Figure 5.

of a large volume of tributary water that entered all layers, depressing specific conductance at all depths (Figure 3). Weakening of snowmelt runoff inflow by the end of July was followed by gradual convergence of conductance across layers caused by erosion of the thermocline (Figures 4 and 5). Water exiting the lake (Figure 5) was drawn primarily from the bottom 5 m of the water column. Therefore, the hypolimnion showed a substantial advective influence on heat content from the middle of May to the end of July. During this interval, the average total outflow from the lake bottom was approximately equal to the volume of the hypolimnion, and hydraulic residence time reached its lowest level in June (Figure 5, 75 days). In most years, water also passed in small amounts over the spillway (maximum for 35 years, ~3.4% of mixed layer for any given month) from the mixed layer during peak runoff; there was no loss of water from the mixed layer over most of the stratification season.

The mixed layer of Lake Dillon warmed progressively over the 35 years of monitoring (Figure 6 and Table 1, May–December, 0.76 °C/decade, $p < 0.0001$). The annual minimum temperature for 0 and 5 m showed an even stronger trend with similar variance (May–December, 0 m = 1.3 °C/decade, tau = 0.42, $p < 0.0001$; 5 m = 1.3 °C/decade, tau = 0.44, $p < 0.0001$); the annual maximum water temperature for May–December in the mixed layer showed no significant temporal trend. Secular warming of Lake Dillon occurred at all depths, but the rate of warming declined progressively with depth (Figure 6 and Table 1).

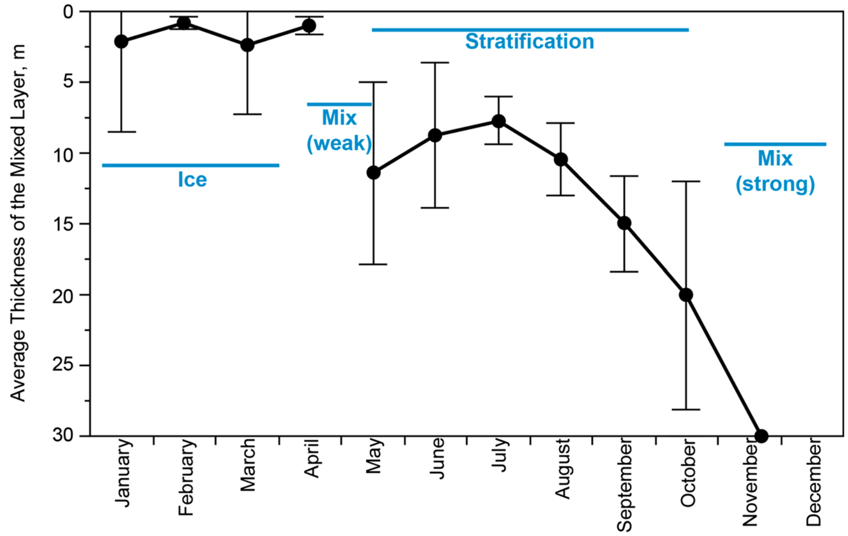

Figure 4. Seasonal features of layering and mixing in Lake Dillon (1981–2016, vertical bars show standard deviations).

There was no evidence of meteorological anomalies, such as those documented for central European lakes in the 1980s (Jankowski et al., 2006; Rempfer et al., 2010; Woolway, Dokulil, et al., 2017).

The mean date of ice off for Lake Dillon was 10 May (±10 days SD, 1986–2016); there was no significant trend across years ($p > 0.05$). Hydraulic residence time had a weak significant positive relationship with date of ice off ($r^2 = 0.16$, change in ice off for minimum versus maximum hydraulic residence time = 14 days, $p < 0.05$). Years of high runoff (low hydraulic residence time) showed prolonged low temperatures for river water entering the reservoir. A stepwise regression that includes both hydraulic residence time and elapsed time since 1981 shows no secular change in date of ice off when residence time is included.

During warm season stratification, flow of tributary waters to the lake affected the hypolimnetic heat content of Lake Dillon through synoptic warming, as shown by temperatures in the lower water column across months (Figure 7). The water column consistently had lowest and interannually constant heat content from January through March. Warming from the surface after March brought the lower water column from 2.5 to 3.0 °C, its winter temperature, up to 4 °C in May. During stratification, the hypolimnion warmed to 6–8 °C, depending on depth. All deep water heat accumulation was lost between mid-November and mid-January during full column mixing; there was no interannual carryover of heat in the reservoir.

The potential for secular warming of the hypolimnion by tributary flow can be determined from temperature data on tributary rivers. Temperature data for rivers were not adjusted for diel temporal variation, as the diel

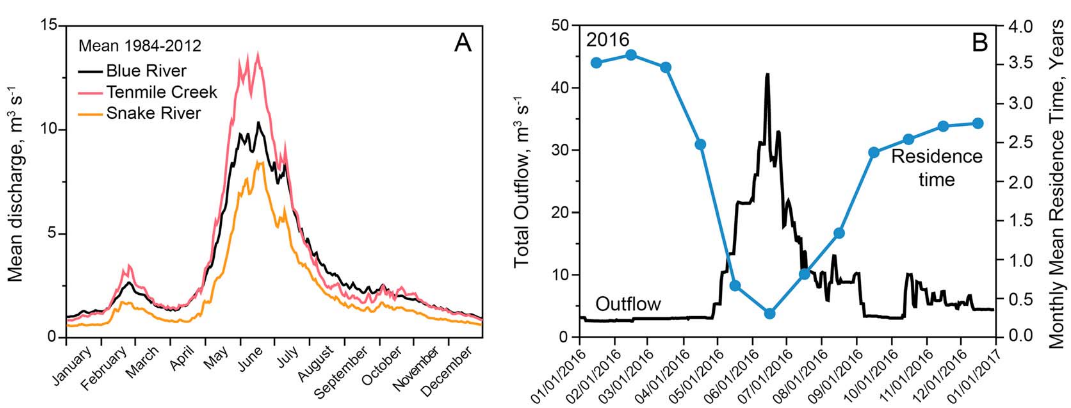

Figure 5. (a) Hydrograph of interannual mean flows for the three river tributaries. (b) Total outflow of water for a year of average runoff from Lake Dillon over an annual cycle (black line) and mean monthly hydraulic residence time for the lake (blue line).

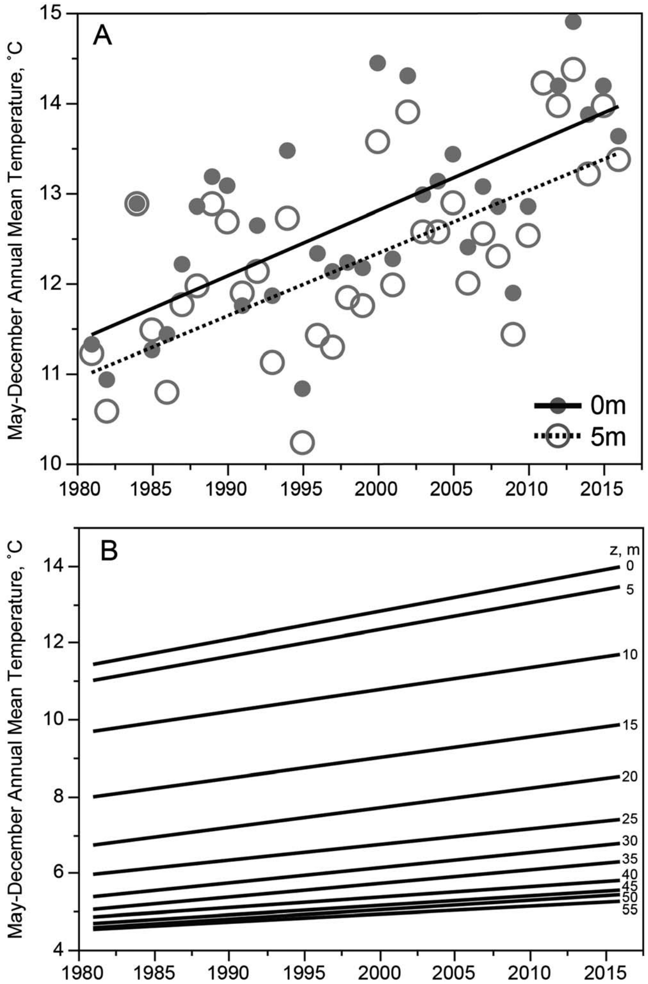

Figure 6. (a) Warming of the mixed layer (0 and 5 m; May–December) for Lake Dillon, 1981–2016. (b) Warming trends for mean temperature at 5-m intervals over the water column of Lake Dillon, 1981–2016.

Table 1
Warming Trends at 5-m Intervals for Lake Dillon, 1981–2016

	Mann-Kendall statistics		
Depth	Kendall's tau	*p*	Sen's slope, Δ°C/decade
0	0.487	<0.0001	0.76
5	0.482	<0.0001	0.75
10	0.370	0.003	0.68
15	0.370	0.003	0.60
20	0.379	0.002	0.55
25	0.338	0.006	0.39
30	0.339	0.007	0.42
35	0.335	0.007	0.37
40	0.277	0.025	0.26
45	0.282	0.022	0.24
50	0.258	0.043	0.26
55	0.267	0.040	0.23

temperature pattern is not known precisely for the sampling locations, but median time of temperature measurements was near midday, which would have been close to the time of diel average temperature (supporting information S1). Warming of the Blue River, which accounts for about a third of the runoff inflow (Figure 5), would explain a significant portion of the post stratification secular warming below the mixed layer. For the June–September interval, the Blue River showed interannual secular mean warming of 1.22 °C/decade (tau = 0.41, $p < 0.01$). The minimum temperature warmed by 1.32 °C/decade (tau = 0.50, p < 0.01), and the maximum temperature showed no trend. Tenmile Creek and the Snake River showed no significant warming.

The monthly position of the maximum density gradient for Lake Dillon did not change across years for the stratification season (days 130–200), nor has the duration of stratification changed (Figure 8).

Mean heat content of Lake Dillon increased across years from May to December (Figure 9a). Consistent warming of the lake over the 35-year interval indicates a secular change in annual heat uptake and loss, which can be defined in terms of the Birgean heat budget (maximum-minimum heat content per year, Figure 9b) across years; the annual heat budget for Lake Dillon increased by approximately 67 cal·cm^{-2}·year^{-1} (0.089 W/m^2). Heat budgets shown in Figure 9b exclude storage and loss of heat caused by formation and melting of ice.

Lake stability showed a strong seasonal pattern corresponding to heat content, as expected (Figure 9c); annual maximum stability showed no secular change across years, but mean stability showed a strong secular increase (trend line extends from 590 to 900 g cm cm/^{2}; 0.058–0.088 J/cm^2, Figure 9d).

4. Discussion

Warming of the Lake Dillon mixed layer, 0.76 °C/decade, greatly exceeded mean warming rates for lakes in general: 0.34 °C (O'Reilly et al., 2015), 0.52 °C (Richardson et al., 2017), 0.20 °C (Schneider & Hook, 2010), projected surface warming of small montane lakes in Colorado (Roberts et al., 2017, 0.47 °C) and a global group of large, deep lakes (Kraemer et al., 2015, 0.20 °C). Warming of Lake Dillon is correlated with regional warming of air temperature (Mast et al., 2011), which is an expected covariant of (O'Reilly et al., 2015; Winslow et al., 2017; Woolway & Merchant, 2017), but not directly responsible for (Fink et al., 2014), warming of lakes. Lake Dillon has responded to warming in unexpected ways with respect to ice off date, mixed layer dynamics, and hypolimnetic dynamics.

4.1. Ice Off

Lake Dillon's high rate of increase in minimum temperature for May–December (1.3 °C/decade) is consistent with studies showing strong effects of warming on date of ice off and duration of ice cover (e.g., Latifovic & Pouliot, 2007; Livingstone et al., 2010; Magnuson et al., 2000), but Lake Dillon did not show a trend in date of ice off. Changes in date of ice off are predictable from meteorological data (Hewitt et al., 2018), but mechanisms affecting date of ice off are not yet clear. In general, the rate of change in ice off date in relation to change in minimum lake temperature is small and shows interannual irregularity that may mask directional changes over records of only a few decades. The mean

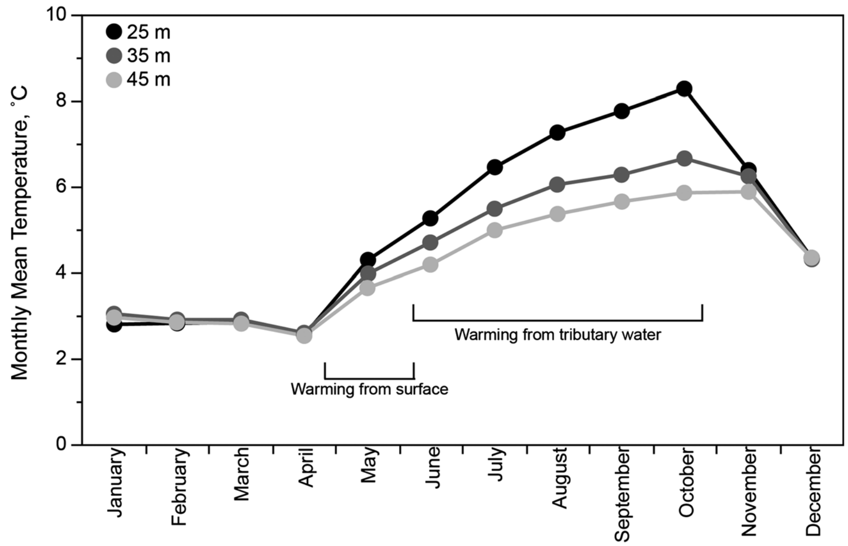

Figure 7. Mean monthly hypolimnetic temperature for Lake Dillon, 1981–2016 showing timing of vertical heat transport by mixing and heat transport to the hypolimnion by advection.

rate of change documented by Magnuson et al. (2000), for example, based on records of 10 decades or more, averaged only 0.65 days/decade. For the recent past, during which many lakes have shown more rapid change, Hewitt et al. (2018) found earlier ice off dates in nine lakes of Wisconsin and Ontario averaging 1.4 days/decade; Latifovic and Pouliot (2007) documented a decrease of 1.8 days/decade for 20 Canadian lakes over 54 years; an overview by Hewitt et al. (2018) also shows data consistent with small changes per decade in date of ice off. Changes in minimum temperature also can occur over an extended interval without a detectable change in date of ice off. For example, in a study of lakes of varied size and depth in the northeastern United States, Hodgkins et al. (2002) concluded that only 11 of 29 lakes showed a statistically significant change in date of ice off. Also potentially important is a likely lower response of ice cover to warming in cold climates (Weyhenmeyer et al., 2004). For Lake Dillon, absence of a detectable trend in ice off date concurrent with significant increase in minimum temperature may be evidence of no trend or of variance that masks a weak trend.

4.2. Dynamics of the Mixed Layer

A reasonable expectation for lakes that experience warming over multiple decades is that their mixed layers will become thinner, unless some other secular influence, such as a sustained change in wind strength (Woolway, Meinson, et al., 2017), has an effect that offsets the effect of warming. The most obvious example is a dimictic lake with substantial hypolimnetic volume at a latitude where ice loss leads quickly to

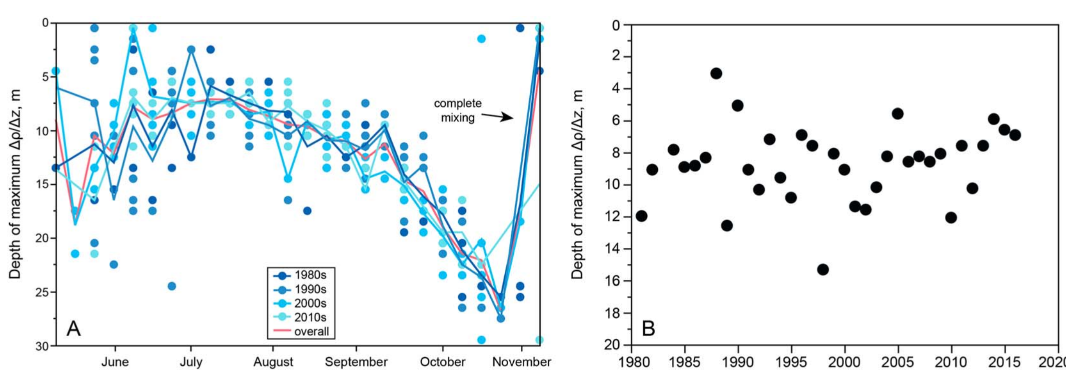

Figure 8. (a) Depth of maximum gradient in water density with depth weekly by decade; (b) mean thickness of the mixed layer across days 130–200 (mid-May to late October) for the 35-year study interval ($p > 0.05$).

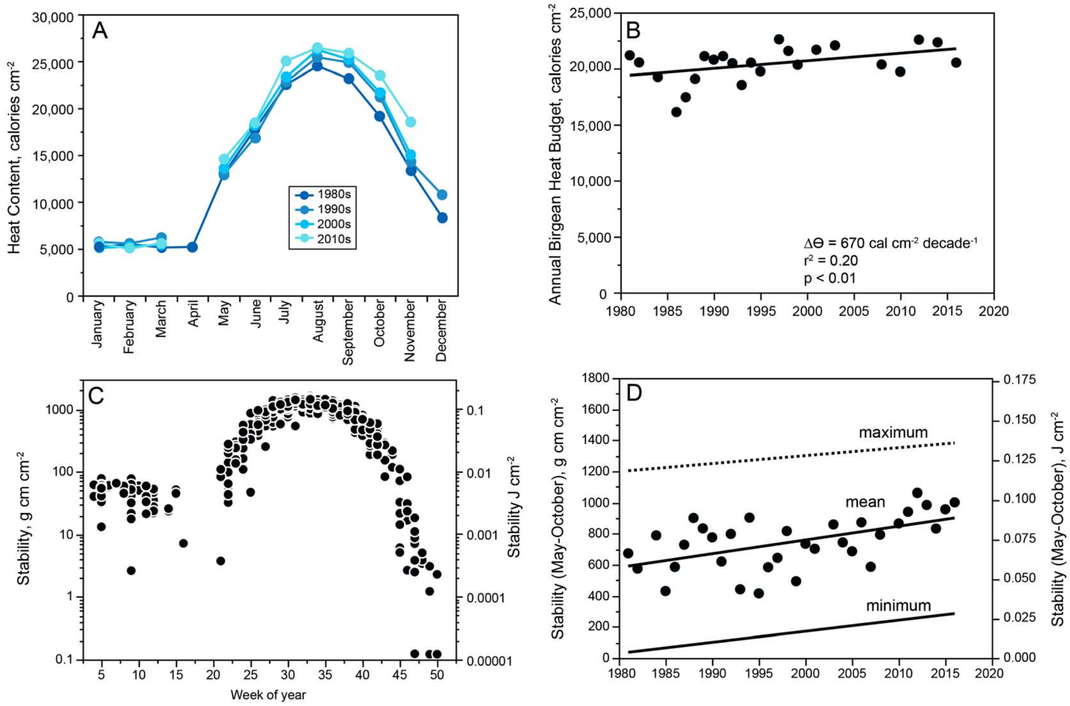

Figure 9. (a) Monthly mean heat content per decade for Lake Dillon. (b) Annual Birgean heat budgets for Lake Dillon. Years with no temperature sampling under ice are excluded. (c) Schmidt stability for all dates (35 years). (d) Stability for May–October (minimum, significant, $p < 0.05$, $r^2 = 0.29$; maximum, not significant, $p > 0.05$; mean, significant, $p < 0.05$, $r^2 = 0.29$).

stratification, thus preserving temperatures near 4 °C in the hypolimnion. With a suite of annual wind strengths showing no consistent change across years, seasonal heat uptake in the upper water column of such a lake would establish a balance, as quantified by the Richardson number (Wüest & Lorke, 2003), between the density gradient caused by warming and current velocity determined by wind. In response to secular warming, a hypothetical dimictic lake in a given month should show interannual thinning of the mixed layer caused by strengthening of the density gradient at the lower boundary of the mixed layer. This line of reasoning, expressed as a model calibrated on the basis of data for Lake Mendota, WI, was published by Robertson and Ragotzkie (1990) and extended by Hondzo and Stefan (1993).

Empirical information verifies that surface warming of lakes significantly correlates with increase in strength of density gradients and stability of the mixed layer, not only for dimictic lakes but also for lakes in general (Kraemer et al., 2015; Richardson et al., 2017). Although information on thickness of the mixed layer is scarcer than information on stability or density gradients, the literature indicates, contrary to early expectation, that increases in strength of density gradients in lakes in response to warming are accompanied by thickening, not thinning, of the mixed layer (Jeppesen et al., 2014; Kraemer et al., 2015).

Clearly the mechanism that determines thickness of the mixed layer is not so simple as it seemed, but no quantitative treatment of the disparity between expectations and observations is yet available. Information on layering in lakes that are warmed mainly by the effects of chromatic dissolved organic carbon (DOC) on transparency (Pérez-Fuentetaja et al., 1999) provides a useful comparison with lakes that are warmed by a change in solar and atmospheric irradiance (a warming effect can be produced by any factor that decreases transparency; Jones et al., 2005, Rose et al., 2016). Lakes warmed by interannual increase in concentrations of DOC show thinning of the mixed layer (Palmer et al., 2014), unlike lakes that lack high degrees of extinction for irradiance. DOC concentrations stabilize absorbance of irradiance in the mixed layer, whereas a mixed layer lacking high extinction of irradiance is more subject to episodic nonseasonal thickening of the mixed layer caused by cool or windy weather. Stabilization of episodic thickening in transparent mixed layers could be enhanced by heat accumulation, which would explain concurrent warming and thickening of the mixed layer.

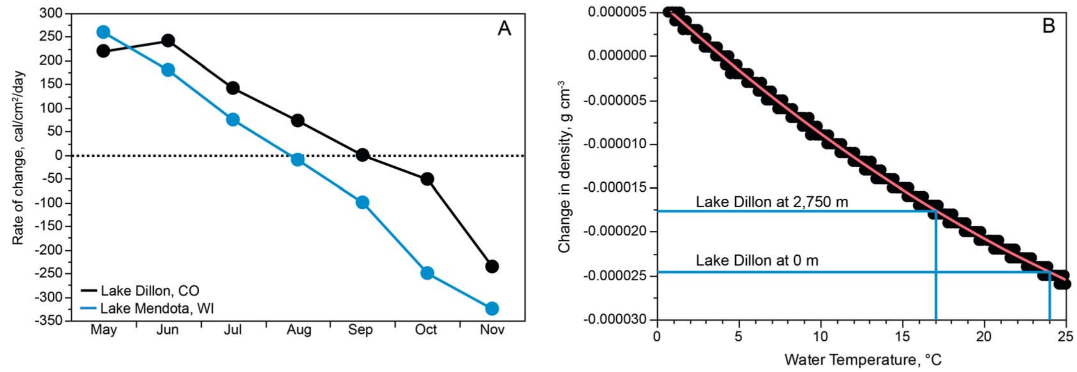

Figure 10. (a) A comparison of mean heat flux per month for Lake Dillon and Lake Mendota, WI (Dutton & Bryson, 1962). (b) Comparison of change in water density per degree Celsius for peak annual surface temperature of Lake Dillon at 2,750 m above mean sea level and at a hypothetical elevation of 0 m.

Given present information on changes in thickness of the mixed layer in response to warming, Lake Dillon should have shown thickening of the mixed layer. The heat budget and temperature of Lake Dillon offer an explanation of the lake's failure to show directional change in thickness of the mixed layer in response to warming. Lake Dillon has high heat fluxes during both warming and cooling phases of the annual cycle, as shown by comparison with heat exchange for Lake Mendota, WI (Figure 12, Dutton & Bryson, 1962). Heat exchange for Lake Dillon is enhanced by elevation, which causes an increase in solar irradiance of ~20% with reference to sea level (Barry, 2001). In addition, low humidity and low particle content of the atmosphere at high elevation (Barry & Carleton, 2003) increase radiant heating of the lake from the atmosphere and back radiation from the water surface to the sky. The importance of these heat exchanges is shown by Fink et al. (2014) for a perialpine lake in which warming was accounted for almost equally by increase in direct solar irradiation and longwave radiation from the atmosphere; incoming heat was balanced by increased back radiation from the water surface and increased evaporation.

High heat fluxes are consistent with significant changes in stability of the mixed layer, as indicated by the steep intermonthly change in thickness of the mixed layer that is typical of Lake Dillon (Figure 8). Warming in May and June led to stabilization of the mixed layer in July, which showed the lowest interannual variance in thickness of the mixed layer; in all subsequent months the mixed layer thickened substantially, but with high interannual variance for thickness in all months leading to overturn (Figure 8). Formation of stable stratification was late in the warming season, as expected for lakes at high elevation (Woolway et al., 2015).

The effect of high and variable daily heat flux on stability of stratification for Lake Dillon was magnified by low mean temperature for the mixed layer (Figure 10b). The density difference of water per degree Celsius at maximum temperature of Lake Dillon (17 °C, −0.000018 g/cm^3) is 30% lower than the corresponding mixed layer temperature that would be expected at sea level (24 °C, −0.000024 g/cm^3; Lewis, 1987). Therefore, synoptic warming of Lake Dillon was less effective in changing density gradients than would be the case for an identical lake at the same latitude but low elevation. Based on long data records for 26 globally distributed lakes, Kraemer et al. (2015) found that warm lakes have stronger responses (thickening) of the thermocline depth to warming than do cool lakes, presumably because temperature change causes less density change at low temperatures. Dynamics of the mixed layer in Lake Dillon are consistent with the hypothesis that the coolest lakes have higher interannual variance in thermocline depth than warmer lakes (Livingstone et al., 2005). High variance in lakes at high elevation is a by-product of irregularity in weather, which affects heat flux significantly on a week-to-week basis. For Lake Dillon, rapid seasonal change in thickness of the mixed layer coupled with high variance in month-to-month position of the mixed layer boundary would likely obscure an interannual trend in thickening of the mixed layer that could have been evident if both the rate of change and variance of mixed layer thickness had been smaller.

The weak or negligible connection of mixed layer depth to synoptic warming for Lake Dillon occurs by a mechanism inverse to the one documented by O'Reilly et al. (2003) for stabilization of the mixed layer in Lake Tanganyika, where the water column temperatures range only over ~23.5–24.5 °C. A small amount of climatic warming changed the stability of the mixed layer for Lake Tanganyika because warmth produces an amplified density gradient in water at high temperatures (Figure 10). Greater stability in the upper water column suppressed nonseasonal vertical mixing that is critical to replacement of bioavailable nutrients in the mixed layers of tropical lakes such as Tanganyika (Lewis, 1987, 1996, 2010). In Lake Dillon, the density gradient separating layers was weak, which caused the mixed layer boundary to respond quickly to heat loss but at an irregular rate based on week-to-week changes in heat flux.

4.3. Dynamics of the Hypolimnion

Dimictic lakes of moderate to great depth, small fetch or a high degree of wind sheltering (Winslow et al., 2015), or high light extinction (Palmer et al., 2014) can be expected to show stable hypolimnetic temperatures concurrent with secular warming of surface water. Shallow dimictic lakes, along with lakes that are warm monomictic (Livingstone, 2003) or polymictic (Richardson et al., 2017), are likely to warm progressively at the time of deepest mixing and to show preservation of deep warming through the stratification interval when the hypolimnion is isolated from the mixed layer (Richardson et al., 2017). Deep lakes in general show low rates of warming (Kraemer et al., 2015).

The expectation that dimictic lakes of moderate to great depth will show little hypolimnetic warming, as forecast by modeling, has been demonstrated empirically. Richardson et al. (2017) found considerable variance but no temporal trend in hypolimnetic temperatures for lakes of northeastern North America. The morphometric features and location of Lake Dillon indicate that it should not show significant hypolimnetic warming, but hypolimnetic warming has occurred. Warming can be explained by annual replacement of hypolimnetic water with river water, which is subject to warming in response to climate change.

River water entering the lake after spring mixing was vertically dispersed; it did not follow a narrow path within the hypolimnion (Figure 3, and similar graphs for individual years). The vertical gradient of warming within the hypolimnion indicates that the entering water had a significant tendency to enter the upper part of the hypolimnion, as would be expected, given that deepest water had the highest density but without narrow confinement. Dispersal of entering water under the influence of turbulence generated by inflow, combined with removal of the coldest water from the deepest point in the reservoir, led to an annual gradation of warming from the upper to the lower part of the hypolimnion (Figure 6, supporting information S2). The hypolimnetic density gradient was very weak but was sustained during stratification because a hypolimnion, beyond its spatial interfaces, has negligible turbulence (Wüest & Lorke, 2003).

Effects of climate warming have not been studied previously in reservoirs. It is likely that reservoirs in general will show interannual hypolimnetic warming by advective exchange, as does Lake Dillon. Advective heat exchange (both input and output) contrasts with radiant surface warming in that it can directly affect the amount and distribution of heat of the hypolimnion during stratification, whereas radiant heat gain affects the hypolimnion by warming the lake as it mixes, before or after hypolimnion formation. In many reservoirs, mechanisms of warming may likely have a hybrid origin involving radiant heat uptake during mixing and hypolimnetic advective warming during stratification.

5. Conclusions

The purpose for study of the 35-year temperature record for Lake Dillon was to determine (1) whether the climate warming of Lake Dillon was affected significantly by its status as a reservoir with deepwater withdrawal and (2) whether warming of Lake Dillon would be affected by its high elevation, which is greater than for other lakes that have been studied over the full water column for responses to climate warming.

The data analysis shows that advective heat transfer by addition and withdrawal of hypolimnetic water causes both vertical thermal gradation and interannual warming of the hypolimnion that would not have occurred in a natural lake of similar morphology. For reservoirs in general, the effect of advection involving both addition and removal of water from the hypolimnion during the period of stratification could be similar to that of Lake Dillon or could be superimposed on changes in hypolimnetic temperatures that may result from warming of the full water column during the mixing season, as is the case for natural lakes.

The high elevation of Lake Dillon is associated with high heat fluxes for both warming and cooling phases and weak density gradients for the mixed layer caused by small rate of change in water density that accompanies temperature changes at low water temperatures. Together, these two influences on the mixed layer caused a steep seasonal increase in thickness of the mixed layer beginning near the end of July and

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extending to full mixing in November. Seasonal thickening of the mixed layer showed high variance across years for a given month because of the sensitivity of its density gradient, which is weak relative to gradients of lakes at the same latitude but lower elevation, to changes in heating and cooling of the mixed layer, and to wind generated current velocities. Month-to-month descent of the mixed layer boundary shows high interannual variance that obscures any tendency toward significant secular change in the mean thickness of the mixed layer. Rapid, irregular change in thickness is likely a general feature of lakes at high elevation. At some critical degree of secular warming, however, lakes at high elevation may show changes in layering reflective of those now documented at lower elevations.

Acknowledgments

We thank the Summit Water Quality Committee and the Denver Water Department for their support of Lake Dillon monitoring, the Rotary Club of Summit County for permission to use its data on annual timing of the ice-free condition for Lake Dillon, and Mike Jones and Doug Robertson helping us work with gravity. Reviewers made comments that allowed us to improve the manuscript. Data used in preparation of this manuscript can be found in the supporting information.

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